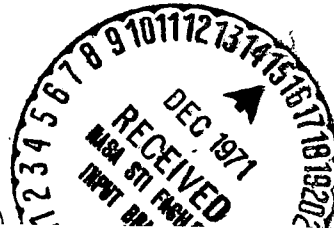


COMPUTATION OF THE WIDEBAND MICHELSON INTERFEROMETER FOR FAR
INFRARED RADIATION

V. M. Charugin and G. B. Sholomitskiy

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ABSTRACT. The authors produce computations to show in what respects the interferometer referred to in the title will surpass ones of monochromator type in measuring and distinguishing the spectra of faint radiation sources.

The Michelson interferometer, like the Fourier spectrometer, possesses greater luminosity and greater ratio of signal to noise without reduction of spectrum resolution, as compared to instruments of the monochromator type [1, 2]. These advantages, despite the need for supplementary computations on an electronic digital computer, are decisive for the application specifically of Fourier spectrometers in the measurement of the spectra of faint extended sources of cosmic radiation. Among the latter fall the relict radiation of the universe, the total radiation of galaxies, and the emission of interstellar gas in the infrared and far-infrared region. For these studies one requires Fourier Spectrometers having a broad passband¹. At the same time, existing beam separators on the basis of dielectric films and wire lattices ensure the coverage of no more than one and one-half octaves as regards frequency [3].

In the present note we compute the characteristics of the dielectric interferometer proposed in study [4] and possessing, in addition to the high luminosity noted in [4], a decidedly broad frequency band over which effective separation of the entering beam takes place. For an interferometer having a

¹We may note, for example, that the major portion of relict radiation is comprised within the wavelength interval from 5 mm to 500 microns.

*Numbers in the margin indicate pagination in the foreign text.

dielectric with an index of refraction of 4.0 we present the frequency characteristic of the separator and the dependence of amplitude of interference upon the angular aperture of the instrument, and also the instrumental function and its distortion at very high angular aperture.

Measurements of low temperature (approximately three degrees Kelvin) relict radiation are possible only on the condition that the measuring instrument be refrigerated to helium temperatures. At a temperature of 4.2°K such semi-conductors as for example, germanium and silicon, behave as dielectrics having a high index of refraction and very low losses [5]. Let the separation of rays take place within a germanium monocrystal ($n = 4$) at a narrow gap parallel to the diagonal plane (Figure 1), and let the interfering rays be collected by a mirror and registered by a broad-band collector also within the dielectric. If isotrope radiation having spectrum brilliance $B(\nu)$ is not polarized, and if the collector is not sensitive to polarization, then upon the moving of one of the halves of the cube along a gap of constant width the variable part of the signal at output (the interferogram) will have the form:

$$I(\Delta) = 2S \int_0^{\Omega_m} d\Omega \int B(\nu) \chi(\phi, \theta, \nu) A(\phi, \theta, \nu) \cos(2\pi\nu\Delta n \cos\psi) d\nu. \quad (1)$$

Here ϕ and $\psi = \arcsin(\sin \phi/n)$ are the inclination of the rays relative to the axis of the beam outside and inside the dielectric, θ is the azimuthal angle of the ray, Δ is the optical path difference, $\Omega_m = 2\pi(\bar{1} - \cos\phi_m)$ is the aperture /5 solid angle, the maximum value of which is limited by the feed optics or the dimensions of the radiation sources; S is the area of the intake aperture.

$\chi(\phi, \theta, \nu) = 1/2(P + T)$ is the efficiency of the separator, P and T are respectively the coefficients of reflection and of transmission of the gap in accordance with intensity for two orthogonal polarizations; and $A(\phi, \theta, \nu) \approx \bar{1}$ is a multiplier which takes into account the inequality of the amplitudes of the interfering rays.

The frequency dependence of efficiency of separation $\chi(\nu)$ was computed by us for an axial beam ($A = \bar{1}$) in a dielectric having $n = 4.0$. The coefficients of reflection and transmission for both polarizations were taken from [6]. As will be seen from Figure 2, the separator has a broad passband fitting the interval $(3 \cdot 10^{-3} - 10^{-1}) \cdot d$, where d is the breadth of the gap in the dielectric. The great relative frequency coverage, constituting no less than 30 (at the 0.5 level) for unpolarized radiation, is occasioned by the separation, in accordance with frequency, of the maxima of efficiency of separation for two orthogonal polarizations by $(n^2 - 1)12$ times, i.e., by 7.5 times when $n = 4$. Evidently the long-wave fall of the characteristic is occasioned by the disappearance of full internal reflection as wavelength rises, and the short-wave fall is occasioned by the disappearance of tunnel effect as the radiation wavelength decreases.

In Figure 26 we also show the characteristic of a film separator of the form $\sin^2(\pi\nu/2\nu_0)$, where the frequency of the tuning of the separator is $\nu_0 = \sqrt{n^2 - \sin^2\phi}/4n^2d$. A comparison of the characteristics in Figure 2 shows that for a frequency coverage of about 30 times no less than three ordinary film separators will be required. /6

The permissible angular aperture and the luminosity of a dielectric interferometer increase by n^2 times as small angles are approached, i.e., at high spectrum resolution $P = \nu/\delta\nu$ ($\delta\nu$ is the spectrum resolution element). Thus the classical Jacquinot limit $\Omega_m R \leq 2\pi$ [1] is converted into $\Omega_m R = 2\pi f(n)$, where the function $f(n) = n^2$ also slowly diminishes with increase of Ω_m at small-angle aperture. In Figure 3 we show the normalized dependence of the depth of modulation (contrast) of interference bands upon angular aperture ϕ_m for germanium (a) and air ($\delta = b$) interferometers, calculated according to the formula

$$V(\phi_m) = \frac{1}{(1 - \cos\phi_m) \cos(2\pi\nu_0 n \Delta_m)} \int_0^{\phi_m} \cos(2\pi\nu_0 n \Delta_m \cos\psi) \sin\psi d\psi. \quad (2)$$

with identical maximum path difference $n\Delta_m = 1$ cm and spectrum resolution $P = 100$ for maximum frequency, the permissible angular aperture, determined at the 90% contrast level, for curve 3a exceeds by more than 4.5 times what is permissible for curve 3b (Figure 3). Since the signal from the isotrope background rises as the square of this ratio, the gain in the signal/noise ratio comes to about 20.

From the standpoint of possible distortions of the interferogram at high angular aperture and computed spectrum of input signal, a direct computation of instrumental function and a determination, in accordance with its distortions, of maximum permissible angular aperture are of interest. In Figure 4 we show the instrumental function of a dielectric interferometer /7/

$$W(\nu - \nu_0) = \frac{1}{(1 - \cos \phi_m)} \int_0^{\phi_m} \frac{\sin 2\pi \nu_0 n \Delta_m (\nu / \nu_0 - \cos \psi)}{2\pi \nu_0 n \Delta_m (\nu / \nu_0 - \cos \psi)} \sin \phi d\phi \quad (3)$$

for a number of angular apertures. It is easy to see that all the way up to $\phi_m = 14^\circ$ shift in the scale of frequencies and expansion of instrumental function for measurement with resolution not higher than $R = 200$ are still not great, whereas for an ordinary instrument having $n = 1$ instrumental function at such angles practically does not exist.

Thus the dielectric interferometer examined can, in combination with broad-band collectors (for example, with a germanium bolometer refrigerated with liquid helium [7]), afford the possibility of registering the spectra of faint extended objects over a broad band of frequencies (5-6 octaves). To be sure, realizing the advantages of the dielectric interferometer, aside from the difficulty of creating it under circumstances of cryogenic temperatures, calls for substantial expansion of the dynamic diapason of the existing registering apparatus.

The dielectric interferometer may be used not only for measuring the uninterrupted and linear spectrum of the cosmic background, but also for securing the spectra of discrete sources over the whole far-infrared

field of 30 to 1,000 microns with a resolution of about 100 at maximum frequency in the diapason of wavelengths under analysis.

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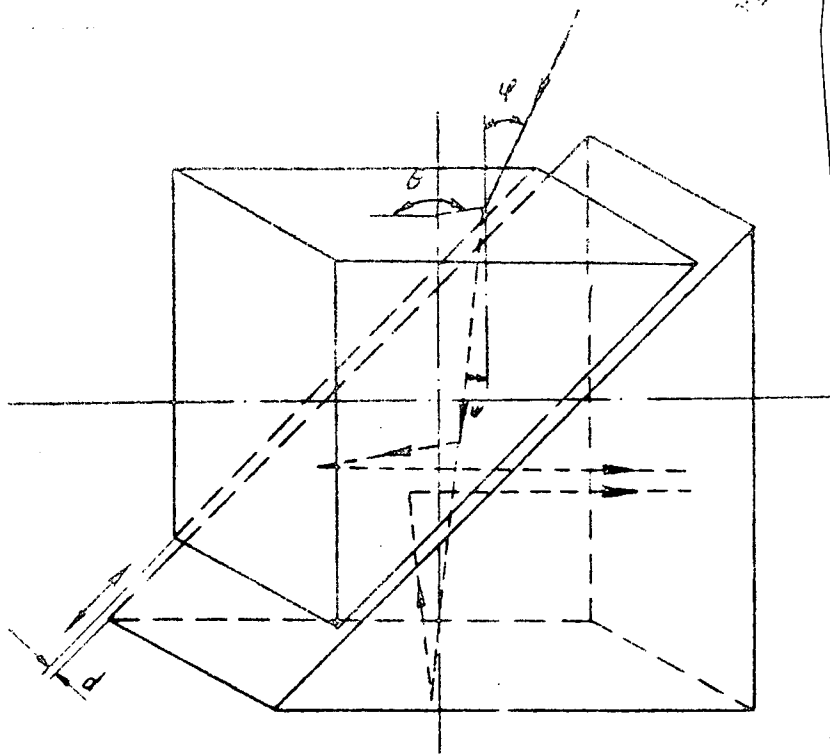


Figure 1.

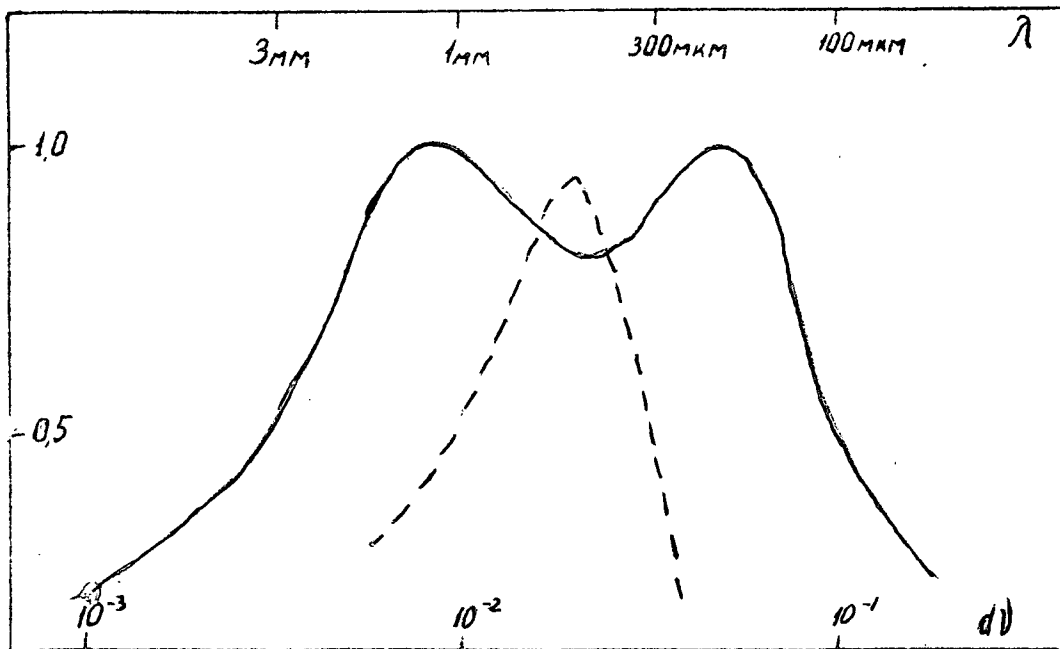


Figure 2.

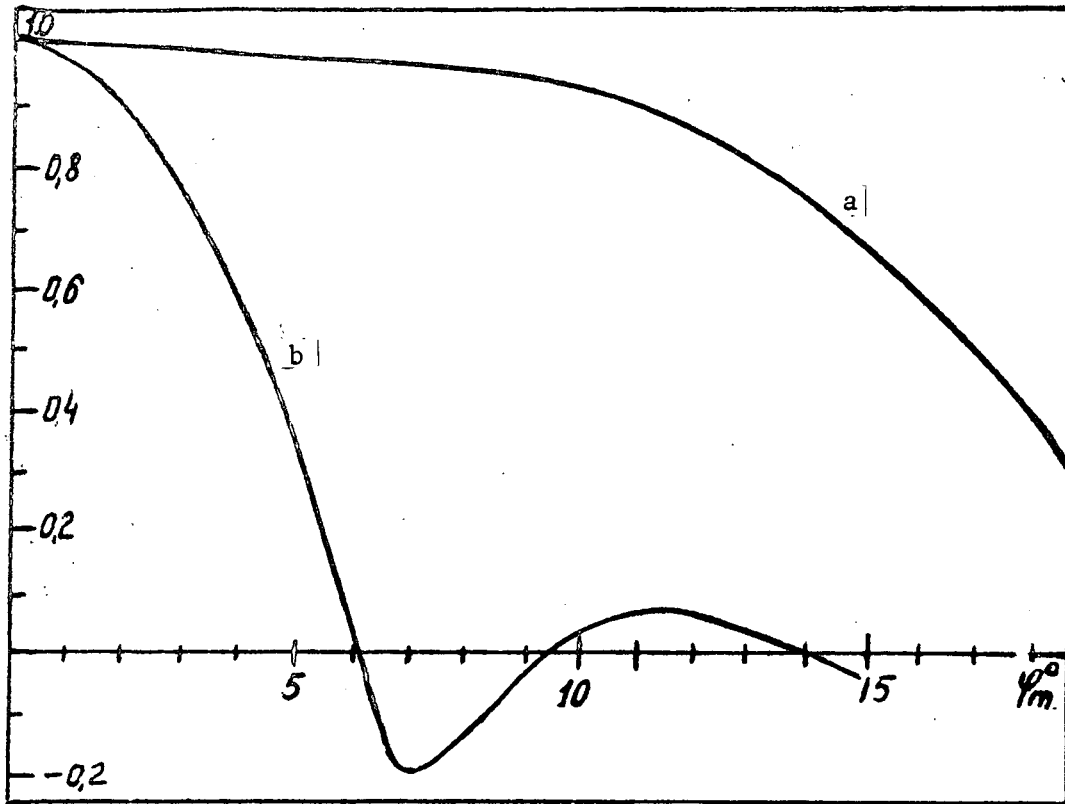


Figure 3.

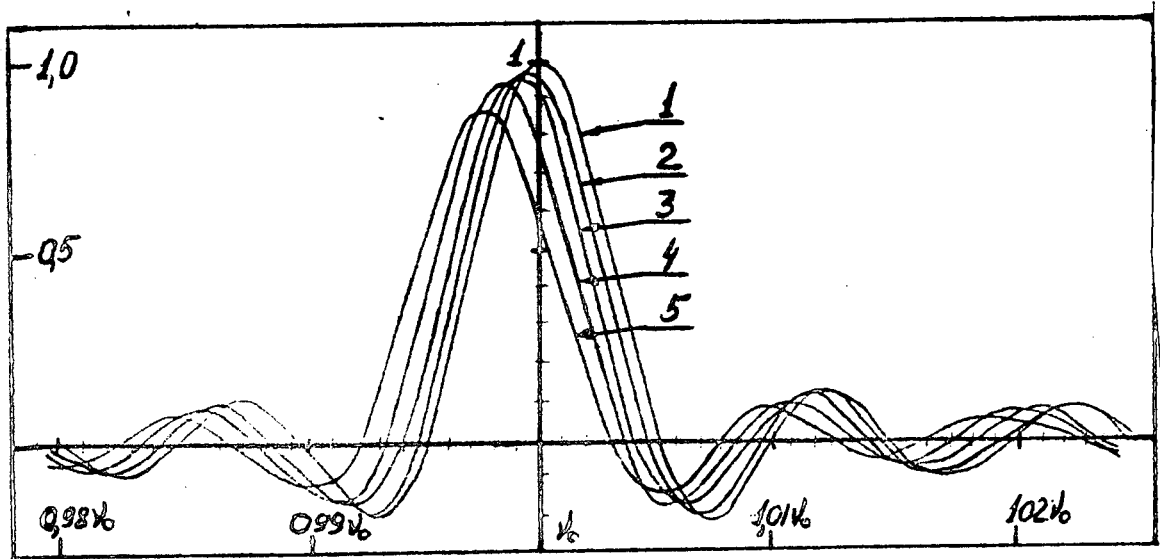


Figure 4.

Captions to Figures

Figure 1. Diagram of Interferometer, Path of Rays and Basic Symbols.

Figure 2 a. Frequency Characteristic of Dielectric Interferometer Having Tunnel Separator at $n = 4$ for Axial Beam.

b. Frequency Characteristic of Ordinary Dielectric Film Separator. The numbering of the axis of the abscissa in lengths of wave (above) is valid for Figure 2 a with $d = 10$ microns and for 2 b with thickness of film $d = (125 \cos \psi / n)$ microns. One should bear in mind the fact that absolute effectiveness of separation (relative to the input point) is half as great in case 2 a as in case 2 b.

Figure 3. Diminution of Amplitude of Interference (Degree of Contrast) with Increase of Angular Aperture for $n \nu \Delta_m = 100$: a) $n = 4$, b) $n = 1$.

Figure 4. Instrumental Function of Michelson Dielectric Interferometer ($n = 4$) for Angular Apertures: 1 -- $\phi_m = 0^\circ$; 2 -- $\phi_m = 10^\circ$; 3 -- $\phi_m = 14^\circ$; 4 -- $\phi_m = 19^\circ$; 5 -- $\phi_m = 24^\circ$.

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